

# The Distribution of Carbon in the Outer Solar System: New Constraints on Planetary Formation Mechanisms from Groundbased Spectroscopic Observations of Uranus and Neptune

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New limits on the methane mixing ratio within the well-mixed troposphere of Uranus and Neptune place significant constraints on planetary formation mechanisms within the outer solar system. Utilizing the recently-derived hydrogen line parameters of Ferguson *et al.* (*J. Mol. Spec.* 160, 315-325, 1993), including lines strengths, pressure shifts, and pressure broadening coefficients for the 4-O S(0) and S(1) lines, and using Voyager thermal structure and helium abundance constraints, we find that the visible troposphere of these planets are significantly deeper than previously derived from similar analyses of hydrogen quadrupole lines (e.g., Baines and Bergstralh, *Icarus* 65, 406-441, 1986; Baines and Smith, *Icarus* 85, 65-108, 1990), resulting in a concomitant decrease in the methane mixing ratios in these planets. Specifically, we find deep-atmosphere methane molar fractions of  $0.016^{+0.007}_{-0.005}$  and  $0.022^{+0.005}_{-0.006}$  for Uranus and Neptune, respectively. Given the Voyager-derived helium mixing-ratio of 0.15 for both planets (Conrath *et al.*, *J. Geophys. Res.* 92, 15003-15010, 1987; Conrath *et al.*, *J. Geophys. Res.* 96, 18907-18919, 1991), we find the abundance of carbon relative to hydrogen is  $20^{+9}_{-6}$  and  $28^{+7}_{-8}$  times the solar value of  $4.7 \cdot 10^{-4}$  derived by Lambert (1978, *Mon. Not. Roy. Astron. Soc.*, 192, 249-272). This carbon enhancement, although significantly less than the  $\sim 50$  times solar abundance derived previously, nevertheless supports the core instability hypothesis of planetary formation (e.g., Mizuno *et al.*, *Progr. Theor. Phys.* 60, 699-710, 1978; Bodenheimer and Pollack, *Icarus* 67, 391-408, 1986). In particular, following the Pollack *et al.* (1986, *Icarus* 67, 409-443) formulation for the dissolution of planetesimals in the envelopes of the forming giant planets, we find that at least 6% of the mass of proximate carbon-containing icy planetesimals was dissolved in the envelopes of Uranus and Neptune before the planets reached the critical mass for runaway gas accretion. Moreover, we find that a comparable proportion of planetesimal material contributed to planetary accretion at 20 and 30 AU. Together these results support the conclusion of Pollack *et al.* that a nontrivial amount of methane in the outer solar system was incorporated into the planets by dissolution of carbon-bearing planetesimals during the early evolutionary stages of both Uranus and Neptune.